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A probabilistic approach to CPTU interpretation for regional-scale geotechnical modelling

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ABSTRACT: The paper describes part of a study carried out to develop the geotechnical model of a coastal area on the Adriatic Sea, between the municipalities of Cesenatico and Bellaria-Igea Marina in the Emilia-Romagna region (Italy). A large experimental database, provided by the Geological, Seismic and Soil Survey of the Emilia-Romagna Authority, was used to develop a stratigraphic model of the upper 30 m subsoil of this coastal area, together with estimates of the mechanical parameters of the different soil units. A Bayesian approach was used to identify the most probable number of soil layers and their thicknesses, based on the Soil Behaviour Type Index obtained from CPTU results. This tool has already been used for small scale areas and its implementation in large datasets could eventually provide a preliminary estimate of the expected soil conditions at a site, taking into account statistically the inherent spatial variability in a rational and transparent way.

1 INTRODUCTION

A joint study focusing on the coastal plain facing the Adriatic Sea, in the southeastern part of the Emilia-Romagna Region, was carried out in cooperation with the Geological, Seismic and Soil Survey (GSSS) of the Emilia-Romagna Authority (RER), leading to a preliminary geotechnical model of this area (Tonni et al. 2016). The investigated territory, approximately 12 km long and 10 km wide, includes the municipalities of Cesenatico, Gatteo, San Mauro Pascoli, Savignano sul Rubicone and Bellaria-Igea Marina, which are well-known touristic sites and generally highly populated areas. This paper uses a dataset of borehole (BH) logs and piezocone (CPTU) measurements provided by the GSSS in order to develop a geotechnical model at a regional scale, also accounting for the depositional environment of the different soil units detected in the area. In particular, a Bayesian approach has been applied to cone penetration data for stratigraphic profiling purposes.

It is worth observing that Bayesian approaches have been successfully adopted for probabilistic geotechnical characterization in a number of contributions (e.g. Wang & Cao 2013, Wang et al. 2016, Cao et al. 2016) and a variety of applications, dealing with the evaluation of geotechnical model uncertainty (e.g. Zhang et al. 2012) or back analysis of soil parameters (e.g. Juang et al. 2013, Chiu et al. 2012), can be found in the literature.

As for geotechnical site investigations, most of these studies focused on quantifying uncertainty in the geotechnical parameters, seldom paying attention to soil stratification except for a few contributions, such as those proposed by Cao and Wang (2013), Wang et al. (2013, 2014), Houlsby and Houlsby (2013).

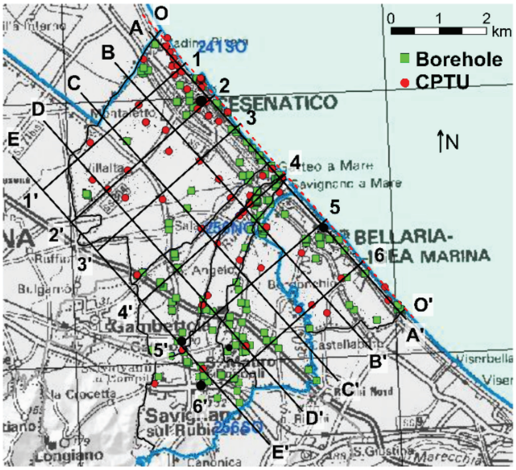

Figure 1. Area of study showing the location of site investigations and the alignments chosen for the cross sections.

2 GEOLOGICAL SETTINGS

Figure 1 shows the geographical boundaries of the study area and the location of the site investigations which form the main part of the available database. The alignments selected for the stratigraphic sections are also reported in the figure.

The local geology consists of the so-called Emilia Romagna Supersynthem (Supersintema Emiliano-Romagnolo, in Italian) which is an alternation of alluvial, deltaic, coastal and marine deposits arranged into different sedimentary cycles driven by transgression-regression of the sea. The thickness of the Emilia Romagna Supersynthem is maximum near the coast and progressively diminishes towards the Apennines. The Supersynthem is subdivided into two lower-rank hierarchic units, namely the Lower Emilia-Romagna Synthem (AEI) and the more recent Upper Emilia-Romagna Synthem (AES), dating back to Middle Pleistocene. The AES is further subdivided into a number of subsynthems, with AES8, AES7 and AES6 being those of interest on the study area. Due to transgressive-regressive depositional sequences, these units are typically characterized by marine and paralic deposits in the lower part and alluvial sediments in the upper part.

In particular, the Ravenna Subsynthem (AES8), outcropping in this area, was deposited after the last glaciation. Its lower boundary dates back to the beginning of the Holocene (10,000 years ago). This geological unit mainly consists of littoral sands and fine-grained alluvial sediments which were deposited by Apennine rivers. The AES8 does not present here any depositional nor erosional gap, except close to the coastline, where the littoral sands are separated from alluvial sediments by an erosional marine scarp formed during the last sea regression. Such littoral belt is 0.5 to 1 km wide, 4 to 12 m thick. In the following, such sandy unit will be indicated as Unit A.

The alluvial formations can be in turn distinguished between deposits characterized by a dense alternation of fine to very fine sands, sandy silts, silts to clayey silts, with a maximum thickness of 3–4 m (fluvial channel deposit, Unit B1), and floodplain deposits. These latter, composed of fine-grained sediments, form a maximum 20 m thick wedge, with locally interbedded clays containing undecomposed organic material. In the following, these sediments will be labelled as Unit B2, when predominantly clayey, and Unit B3, when predominantly silty.

Finally, sand-silt-clay mixtures, arranged in 1 to 6 m thick layers and referable to levee and crevasse deposits, form Unit B4.

3 METHODOLOGY

The experimental database provided by the GSSS includes 140 BH logs, 52 CPTU and 5 seismic piezocone tests (SCPTU), pushed to a depth of 15 to 30 m. In addition, laboratory tests were carried out on approximately 15% of the BHs available, providing soil classification and basic mechanical characterisation. The cross sections were selected to be approximately equally spaced (1.5–2 km), compatibly with the location of the available data. Five longitudinal sections (A-A' to E-E') were taken parallel to a straight reference line running along the coast whilst six cross sections (1–1' to 6–6') were selected in the orthogonal direction, as shown in Figure 1.

The probabilistic soil stratification, i.e. the determination of the number of layers (N) and their thickness (HN = [H1, H2, …, HN]) under a probabilistic framework, was based on the Soil Behaviour Type index, Icn, which is calculated iteratively from the dimensionless normalized cone resistance Qtn and the friction ratio Fr, according to the procedure described in Robertson (2009). The soil classes were then defined in terms of the Soil Behaviour Type (SBTn), corresponding to a well defined interval of values assumed by Icn. To keep the computational time at a minimum, one in five data points were used for the analysis (i.e. every 0.1 m), since this sampling frequency was found to basically guarantee the same reliability in the identification of N and HN obtained with higher rates, despite the risk of including rogue data points. On the other hand, running averaging of the data to remove spurious data had an adverse effect on the standard deviation associated with the identification of boundaries.

Due to spatial variability of soils, Icn fluctuates with depth and this poses a profound challenge in identifying soil stratigraphy (i.e., N and HN) from a single Icn profile with a certain reliability. Under the Bayesian framework, the uncertainty in N and HN estimated from the Icn profile is explicitly quantified using their posterior distributions, reflecting the degrees-of-belief in their estimates. For a given profile of Icn denoted by ξ, the identification of soil stratigraphy can be divided into two steps (Cao et al. 2017):

1. Comparison of the soil stratification models with different numbers of soil layers based on the conditional probability $P(N|\ \xi)$ and determination of the most probable N* among a number of possible N values. Using Bayes' Theorem, $P(N|\ \xi)$ is written as:

$$P(N|\ \xi) = P(\xi|\ N)P(N)/P(\xi) \tag{1}$$

Where P(N) is the prior probability of N reflecting the prior knowledge on N in the absence of CPTU data, $P(\xi)$ is the probability density function of ξ, assumed as constant and independent from N, while $P(\xi|\ N)$ is the conditional probability of ξ given the soil stratification models with N layers, also frequently referred to as the "evidence" for soil stratification models with N layers provided by ξ.

Based on Eq. (1), $P(N|\ \xi)$ is proportional to the evidence $P(\xi|\ N)$, which means that maximizing $P(\xi|\ N)$ with respect to N leads to the maximum value of $P(N|\ \xi)$ and hence N*. Calculation of $P(\xi|\ N)$ is pivotal to evaluating Eq. (1) for quantifying uncertainty in N based on ξ and thus determining the most probable number of layers N*.

2. Evaluation of $P(HN|\ \xi, N)$ for quantification of uncertainty in layer thickness HN based on ξ for a given soil stratification model with N soil layers and determination of their most probable thicknesses H*N and boundaries D*N. Within a Bayesian framework, $P(HN|\ \xi, N)$ is referred to as the posterior distribution of HN based on ξ, and it is expressed as:

$$P(HN|\ \xi, N) = P(\xi|\ HN, N)P(HN|\ N)/P(\xi|\ N) \tag{2}$$

Where $P(\xi|\ HN, N)$ is the likelihood function quantifying information on HN of the soil stratification model with N soil layers provided by ξ, $P(HN|\ N)$ is the prior distribution of thicknesses and $P(\xi|\ N)$ is the evidence for the soil stratification model with N layers, used as a normalizing constant, as it is independent from HN for a given N value. Determination of N* and its corresponding most probable thickness HN* requires the formulation of the likelihood function $P(\xi|\ HN, N)$ and prior distribution $P(HN|\ N)$ as well as calculation of the model evidence $P(\xi|\ N)$. Details on the method can be found in Cao et al. (2017).

Figure 2 shows an example of piezocone logs from a test carried out along the cross section 2–2', together with soil classification results in terms of Icn and SBTn and the soil stratigraphy from an adjacent BH. The SBTn profile reveals a pronounced prevalence of clay-like sediments

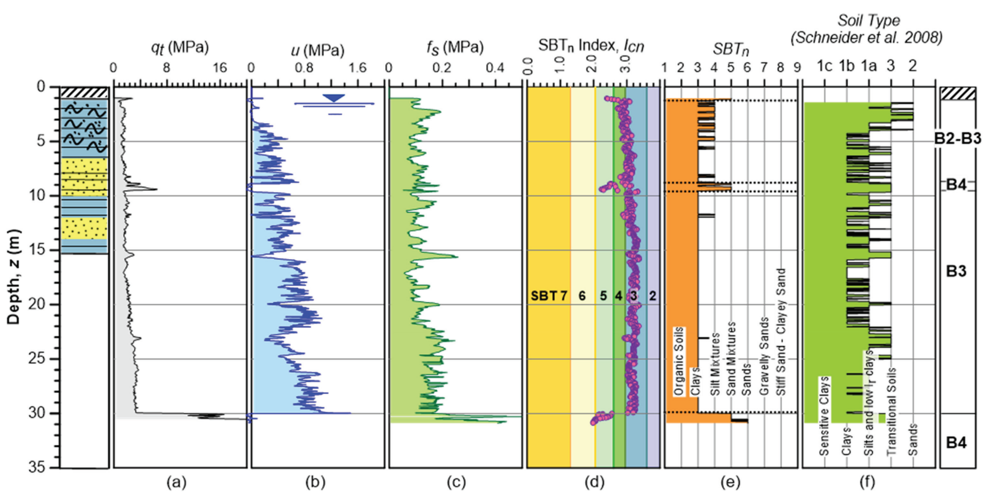

Figure 2. Example of piezocone data and comparison of CPTU-based soil classification results with BH log (CPTU22–4 from cross section 2–2').

(SBTn = 3) from 6 to approximately 30 m in depth, whilst an alternation of silts (4) and clays (3) is observed in the upper 6 meters. Based on the Icn profile depicted in column (d), the figure shows the most probable boundaries of soil layers (horizontal dashed lines in column (e)) provided by the Bayesian analysis. Such boundaries have been identified at 1.22, 8.78, 9.47 and 29.88 m from ground surface, with standard deviations equal to 0.027, 0.107, 0.097 and 0.036 m respectively.

For useful comparison, results from the application of the classification method developed by Schneider et al. (2008) have been reported in Figure 2 as well. This latter approach, which relies on the normalized tip resistance Qt and pore pressure ratio (Δu2/σ′v) for soil classification, has been especially devised to correctly identify intermediate sediments, where partial consolidation is very likely to occur during cone penetration. According to the computed soil type profile (f), a pronounced intermediate nature of fine sediments is observed, with a significant amount of experimental points falling in the domain of silts (1a) and transitional soils (3), these latter including a wide variety of soil mixtures (i.e. clayey sands, silty sands, silty sands with clay, clayey sands with silt).

4 GEOTECHNICAL MODEL

The following analyses focus on the cross section 2–2′, orthogonal to the coast and thus including both Units A and B previously mentioned. Besides, due to gentle sloping of the ground surface, such alignment allows a rather straightforward cross-correlation of in situ test logs.

Four CPTU tests (CPTU22-1 to CPTU22-4 from right to left) and two boreholes (BH22-1 and BH22-2 from right to left) were available for interpretation and are presented as “raw data” in Figure 3(a). Figure 3(b) presents the profiles of the computed Icn and the corresponding SBTn for the whole set of CPTU, together with the indication of the most probable boundaries of soil layers. The associated geological Units, as commented in Section 2, are also reported.

The SBTn profiles generally appear rather uniform in Unit B2, whilst a certain heterogeneity is observed in the other soil layers. A few interbedded coarse-grained layers have been identified in CPTU22-2 and CPTU22-4, which might indicate proximity to abandoned streams.

In this preliminary attempt to apply a Bayesian approach to the available data, the probabilistic identification of soil stratification has been carried out separately for each sounding, in order to have a more robust interpretation. According to results, it generally appears that there is no correspondence across the tests in N and HN, i.e. number and boundaries of layers identified along each vertical. It is worth mentioning here that the proposed soil stratification is coupled with rather low values of the standard deviation, typically in the range 0.001–0.1 m and only exceeding such interval (0.33 m) for the boundary detected at a depth of 21.76 m in CPTU22-2. A combined analysis of the tests would be undoubtedly crucial for the development of a comprehensive 2D and 3D stratigraphic model of the area and is currently in progress.

As a final remark on stratigraphic conditions, it must be observed that the application of the method of Schneider et al. (2008) to the whole set of CPTU confirms the outcome previously commented for CPTU 22-4, i.e. a prevalence of silts and intermediate sediments (1a and 3) rather than clay-like soils (SBTn = 3). In such case, partial drainage may occur during a standard rate CPTU (Tonni and Gottardi 2009, 2010, García Martínez et al. 2016) and this may have a significant effect on the derived soil parameters. Schnaid et al. (2004) have amply discussed the consequences of partial drainage on the undrained strength su, with reference to piezocone data in a natural silty deposit and a tailings deposit from a gold mine, and values of the undrained strength ratio su/σ′v0 have been interpreted in terms of the most likely drainage conditions. It was observed that this effect can result in an overestimation of su values, thus leading to unsafe design.

In what follows, estimates of the undrained shear resistance su in fine-grained soils, as determined from CPTU22-4, are presented. Assuming normally-consolidated or slightly overconsolidated sediments, a cone factor Nkt = 14 has been adopted to convert the CPTU net cone resistance to undrained strength. Figure 4 shows the undrained shear strength calculated in pronounced fine grained sediments (clays, clayey silts, silty clays) located below the water table, thus excluding intermediate soils. Three separate trends can be observed for su within the soil layer from 10 to 30 m in depth (labelled as Layer 4). In particular, when the whole data points are analysed, the computed estimates shows a bimodal frequency distribution (Figure 5). When distinguishing between Unit B2 and Unit B3, clays present a log-normal distribution, while silts/clayey silts follow a bimodal distribution, with significantly high values of su. In this latter case, the computed su must be considered with a great deal of uncertainty, due to potential partial drainage. It is interesting to note how the changes in trend are separated by thin soil layers, classified as transitional, indicating a change in depositional environment.

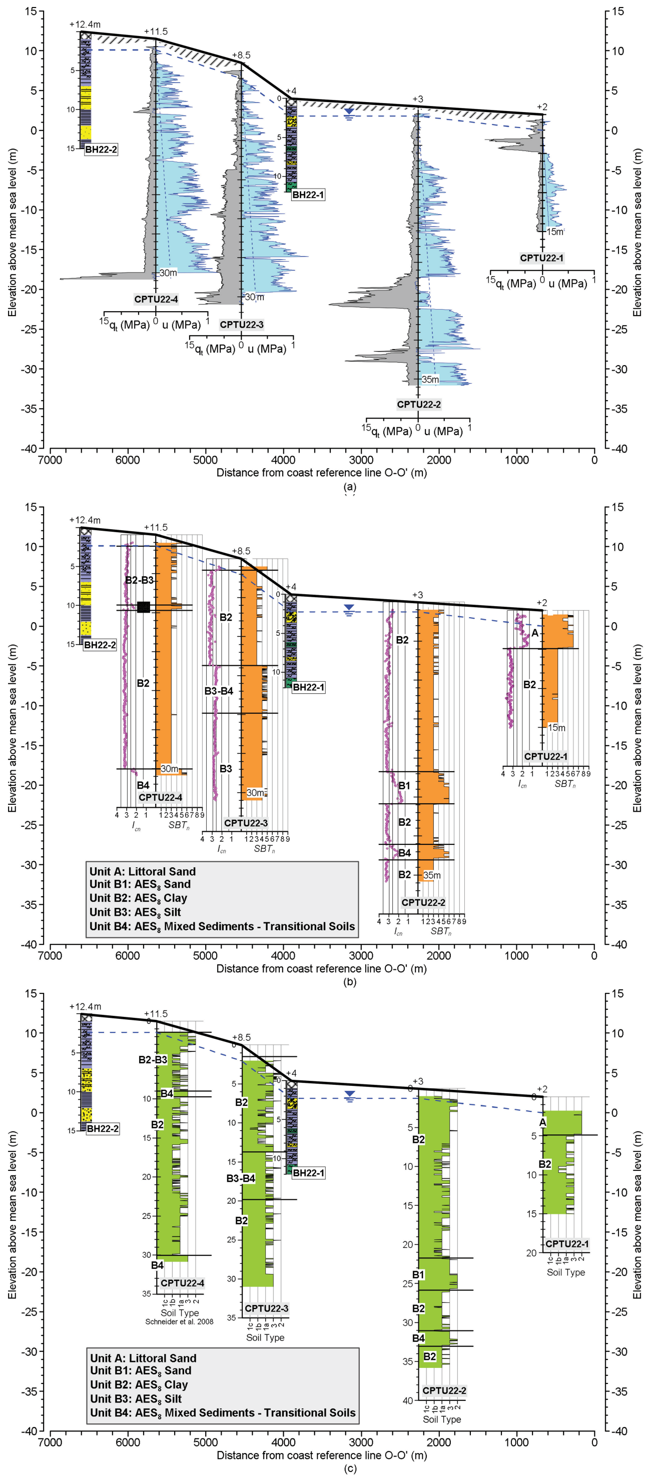

Figure 3. Cross section 2–2’: (a) CPTU test results; (b) Icn and SBTn profiles in conjunction with Unit subdivision; (c) CPTU-based classification results according to Schneider et al. (2008).

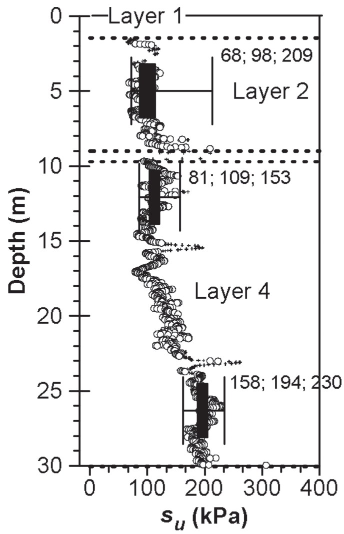

Figure 4. Undrained shear strength for CPTU22.

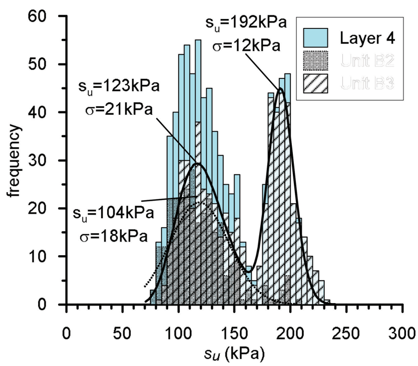

Figure 5. Frequency distribution of undrained shear strength within different soil sub-units.

5 CONCLUSIONS

The paper describes part of a study carried out to develop a regional geotechnical model of the coastal area of the Emilia-Romagna region. A Bayesian approach has been adopted to identify soil stratification from CPTU. Geological information have been also taken into account to help in identifying soil stratigraphy. A few issues on the estimate of undrained shear strength in fine-grained soils from CPTU data are briefly discussed, especially with reference to predominantly silty sediments.

The development of a regional-scale geotechnical model of this area aims at providing guidance on the selection of appropriate tests and correct data interpretation.

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